

# Discovery of an X-ray cavity near the radio lobes of Cygnus A indicating previous AGN activity

Gayoung Chon<sup>1</sup>, Hans Böhringer<sup>1</sup>, Martin Krause<sup>2,1</sup>, Joachim Trümper<sup>1</sup>

<sup>1</sup> Max-Planck-Institut für extraterrestrische Physik, 85748 Garching, Germany

<sup>2</sup> Excellence Cluster Universe, Technische Universität München, Boltzmannstrasse 2, 85748 Garching, Germany

Submitted 3 May 2012;

## ABSTRACT

Cygnus A harbours the nearest powerful radio jet of an Fanaroff-Riley (FR) class II radio galaxy in a galaxy cluster where the interaction of the jet with the intracluster medium (ICM) can be studied in detail. We use a large set of *Chandra* archival data, *VLA* and new *LOFAR* observations to shed new light on the interaction of the jets with the ICM. We identify an X-ray cavity in the distribution of the X-ray emitting plasma in the region south of the Cyg A nucleus which has lower pressure than the surrounding medium. The *LOFAR* and *VLA* radio observations show that the cavity is filled with synchrotron emitting plasma. The spectral age and the buoyancy time of the cavity indicates an age at least as large as the current Cyg A jets and not much larger than twice this time. We suggest that this cavity was created in a previous active phase of Cyg A when the energy output of the Active Galactic Nucleus (AGN) was about two orders of magnitude less than today.

**Key words.** X-rays: galaxies: clusters - Galaxies: clusters: intracluster medium - Radio continuum: galaxies - Galaxies: jets

## 1. Introduction

AGN feedback in galaxy clusters has gained a lot of attention in recent studies, e.g. McNamara & Nulsen (2007). Most of the AGN in clusters are FR I radio sources. In the local Universe Cygnus A is an exception featuring a powerful FR II radio jet in a galaxy cluster where very energetic interaction effects of the jets with the intracluster medium (ICM) can be studied in detail, e.g. Carilli et al. (1996); Clarke et al. (1997); Kaiser & Alexander (1999); Krause (2005). In this object we can observe jets of relativistic synchrotron emitting plasma plowing into the intracluster medium out to a distance of  $\sim 100$  kpc from the nucleus where they end in hotspots clearly seen at radio wavelengths, (e.g. Alexander et al. 1984) and X-ray images (e.g. Harris et al. 1994). The internally supersonic jet plasma is thermalised at these hotspots, which advance only at about 2000 km/s due to the extreme density contrast (Alexander & Pooley 1996). The jet plasma flows away from the overpressured hotspots establishing a backflow. Together with the adjacent ICM, this region defines an overpressured bubble which drives a shock into the undisturbed ICM, first seen by Carilli et al. (1988) in the centre of the Cyg A cluster.

Many aspects of Cyg A have been studied in both radio and X-rays, e.g. Carilli et al. (1994); Wilson et al. (2000, 2006); Smith et al. (2002); Yaji et al. (2010). Some progress has been made recently in modeling these jets with hydrodynamical simulations (Krause 2003, 2005, see also Alexander & Pooley 1996). The observed width of the radio lobes are only reproduced by very light jets, with jet densities of order  $10^{-4}$  times the already tenuous surrounding X-ray plasma. This implies a low momentum flux and low hotspot advance speeds, comparable to the general advance speed of the bow shock driven into the surrounding ICM. Consequently, the bow shock assumes an almost spheri-

cal shape around the radio source with a wide region of shocked ICM adjacent to the radio lobes.

In this paper we use most of the *Chandra* archival data on Cyg A to study in detail the interaction effects in the region near the AGN inside the radio lobes. In this region we discovered an X-ray cavity very similar to those found in FR I radio sources in clusters and investigated it in detail with the X-ray and radio data to unveil its physical properties and its origin, and the interpretation with a hydrodynamical simulation.

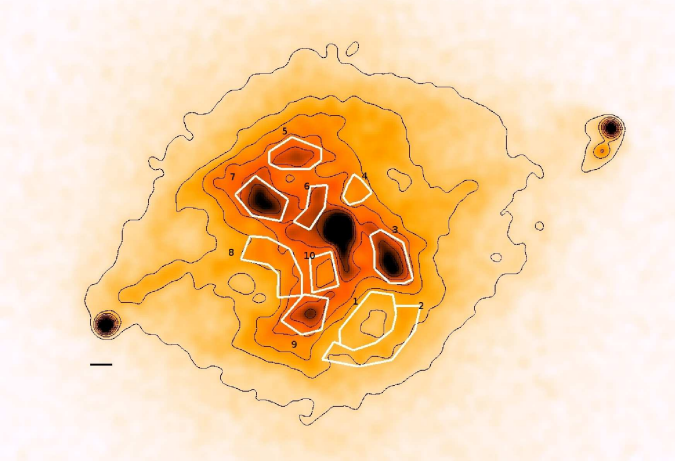
For distance related quantities we adopt a flat  $\Lambda$ -cosmology with  $H_0=70$  km/s/Mpc,  $\Omega_M=0.3$ . For the redshift of Cyg A of 0.0561,  $1''$  corresponds to 1.09 kpc.

## 2. Chandra observations

We used all available archival *Chandra* ACIS-I observations for Cyg A, which sum up to 200 ks of exposure. Standard data analysis was performed with CIAO 4.4<sup>1</sup> with calibration database (CALDB) 4.4.8. This includes flare cleaning by filtering light curves of source-free regions, VFaint mode, gain, and charge transfer inefficiency corrections. The final exposure after cleaning is slightly less than 190ks. We apply the same procedure to an ACIS blank sky observation, which was used as our background estimate after adjusting the normalisation. In our case different normalisations of the background do not significantly influence the results of our analysis since the region of our interest has high source counts. We used the 9–12.5 keV countrate to get the appropriate normalisation for the background exposure. We used *fluximage* to obtain flux and exposure maps after background subtraction, and the combined map is shown in Fig. 1 and 3 in the 0.5–2 keV band. Fig. 1 shows a detailed image of Cyg A with X-ray contours in an area of  $2.6' \times 1.75'$ . There are

Send offprint requests to: Gayoung Chon, gchon@mpe.mpg.de

<sup>1</sup> <http://cxc.harvard.edu/ciao4.4/index.html>



**Fig. 1.** *Chandra* image of Cygnus A with contours and ten study regions in white polygons with their ID numbers. The dimension of the image is  $2.6' \times 1.75'$ , and a black line of length  $5''$  is marked below the eastern hotspot. The X-ray cavity, 1, is the polygon defining a region of low X-ray surface brightness.

ten regions defined by white polygons with their ID numbers, for which we determine the X-ray properties in the next section.

### 3. Properties of the X-ray Cavity

Fig. 1 shows the detailed X-ray surface brightness distribution in the shocked region of Cyg A. The shocked region is contained in an ellipse surrounding two hotspots and the jets, and is extending outside the outermost contour in Fig. 1. From radio observations we know that the energetic jet created backflows, which are seen as diffuse lower surface brightness areas starting near the hotspots towards the centre. The central region away from the heads of the jets and backflows is expected to be in pressure equilibrium. An interesting region drawing an attention is the low surface brightness feature numbered 1. This is the “cavity” we study in this paper with a lower than expected thermal plasma pressure.

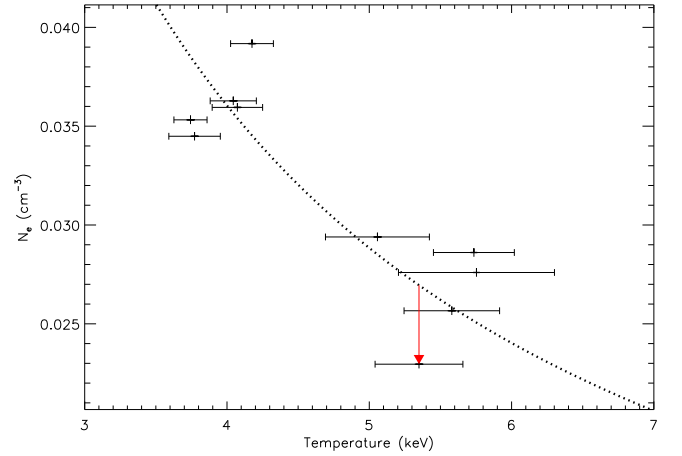
The goal of the X-ray analysis is then to extract spectra for the determination of temperatures, to calculate electron densities,  $n_e$ , and pressures to characterise the cavity and its vicinity to diagnose the pressure distribution.  $n_e$  is derived from the X-ray luminosity,  $L_x = \int dV n_e^2 \Lambda(T)$ , and temperatures are determined by fitting the observed spectrum in XSPEC with an absorbed MEKAL model.

We defined ten regions of roughly homogeneous surface brightness and sufficient source counts in the centre of Cyg A around region 1. For comparison four regions (3,5,7,9) were similarly defined as in Smith et al. (2002); Wilson et al. (2006). Our fitted temperatures from these four regions agree well with theirs within our uncertainties. We find the temperature in region 1 to be  $5.35 \pm 0.31$  keV with a metallicity  $0.81 \pm 0.12 Z_\odot$ , and a column density of  $0.3 \pm 0.02 \times 10^{21} \text{ cm}^{-2}$ . The temperatures and pressures from all regions are listed in Table 1 where the region numbering follows from Fig. 1

To calculate the pressure inside each region a geometry of the volume needs to be assumed, which in principle introduces the largest uncertainty for this work. We assume the shocked region is contained in a cylinder whose length is defined along two hotspots with a radius, 100 kpc. This radius is chosen since

Regions	T (keV)	$\Delta T$ (keV)	P ( $10^{-10} \text{ erg/cm}^3$ )
1 (Cavity)	5.35	0.31	3.77
2	5.58	0.33	4.40
3	3.74	0.12	4.06
4	5.75	0.55	4.87
5	4.04	0.16	4.51
6	3.77	0.18	4.00
7	4.17	0.15	5.02
8	5.73	0.28	5.04
9	4.07	0.17	4.50
10	5.06	0.36	4.56

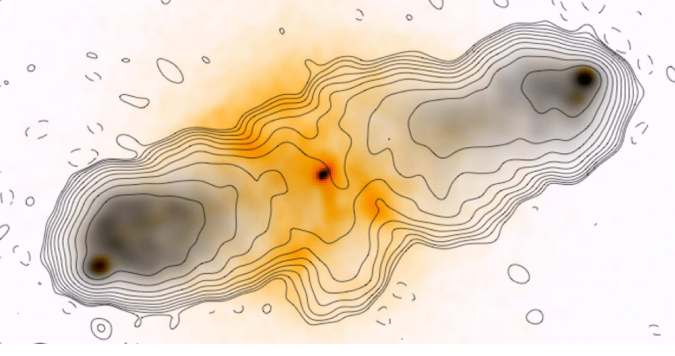
**Table 1.** X-ray temperatures and pressures of the ten regions defined in Fig. 1. The largest uncertainties in the pressure is contributed by the estimated length of the region along the line of sight. For details see text.



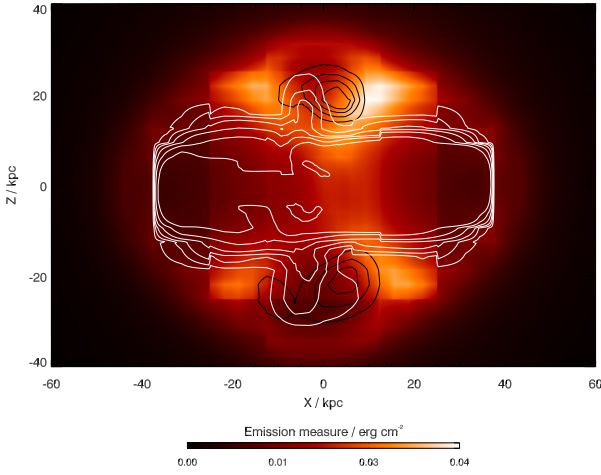
**Fig. 2.** Electron density versus temperature of the ten regions around the X-ray cavity. We expect to have an equi-pressure in the central ICM, which is indicated by a dashed line. The largest departure from the expected pressure is exhibited by the cavity of our study marked by a red arrow.

simulations show the shock radius along the semi-minor axis to be roughly 100 kpc (Krause 2005). The length of each region is then the distance it extends along the line of sight contained in the cylinder. With this definition we calculated the density and the thermal pressure of the ten regions listed in Table 1. We expect all ten regions to be in near thermal pressure equilibrium. However, our findings show that the region 1 contains the smallest contribution from the thermal pressure among ten areas. In Fig. 2 the measured temperature and derived  $n_e$  are plotted with the average pressure equilibrium in a dashed line. The statistical error of  $n_e$  is very small, which is dominated by the geometric assumption about the volume that the electrons occupy. We see that much of the thermal pressure scatters about the expectation, however, the pressure of region 1 has the largest offset, roughly 16 % lower than the expectation. This implies that the volume which the thermal plasma occupies has to be 32 % smaller to be in pressure equilibrium with the surroundings.

Here we continue with the hypothesis that the missing thermal pressure in the volume can be explained by introducing non-thermal pressure support. In the next section we will use this 32 % of the volume to calculate the relativistic plasma and magnetic field properties.



**Fig. 3.** Overlay of a *LOFAR* radio map as contours on the *Chandra* image. The *LOFAR* contours are taken from Fig. 1 of McKean et al. (2011), and the image dimension is  $160'' \times 80''$ . Notably two hotspots and the low surface brightness cavity of our study in the X-ray image matches spatially to the excess in the radio contours.



**Fig. 4.** Simulated X-ray emission measure map of the interaction of two perpendicular jets in Cyg A. The four bright regions are shaped by the cavities of the first jets. The cavities of the main jets are also visible. Black contours show the volume fraction of the first jets at  $2'' \times 10^{-5}$ . That of the main jets is at  $1, 3, 6, 12, 24$  and  $48 \times 10^{-3}$  in white. Rectangular features are due to artifacts of the nested static grid setup.

#### 4. Properties of the relativistic plasma in the cavity

We now search for an explanation of the missing cavity pressure by a non-thermal contribution with radio observation. We compared X-ray images of Cyg A with radio maps from *VLA* and *LOFAR* observations. Two *VLA* observations are at 74 and 357 MHz from Lazio et al. (2006), and the new commissioning *LOFAR* data at 238 MHz is from McKean et al. (2011). The overlay with the recent *LOFAR* observation is shown in Fig. 3. It is obvious that the X-ray cavity perfectly coincides with the radio emission region extending out from the bridge between the radio lobes south of the nucleus. The highest contours trace well the cavity region while the lowest contours encompass also the cavity rim. As was argued in the previous section the missing thermal pressure can be partly explained if 32 % of the cavity volume is filled with relativistic plasma. In this section we cal-

culate the relativistic plasma and magnetic field pressure of the cavity.

Radio observations provide information on the energy loss of the relativistic electrons in a magnetic field through synchrotron radiation. The magnetic field strength is conventionally derived by minimising the total energy content in the volume based on the equipartition argument. The magnetic field energy is proportional to the square of the magnetic field strength while the total electron energy is calculated by integrating the product of its density and energy distribution. The total plasma energy of a volume can then be written in terms of a magnetic field strength,  $E_{tot} \propto \alpha(1+k)LB^{-3/2} + B^2\Phi V/8\pi$  where  $k$  is the ratio of proton to electron energy,  $L$  is the intensity of the radio emission,  $\Phi$  is the filling factor describing the fractional volume that the magnetic field occupies, and  $V$  is the volume of interest (e.g. McNamara & Nulsen 2007). The corresponding pressure of the total energy in relativistic plasma plus magnetic field is then  $13/9 B^2/8\pi$  (Pacholczyk 1970).

The radio flux density and spectral index were determined based on the multi-frequency data mentioned earlier. The luminosities of the cavity are estimated to be 234 and 35 Jansky at 74 and 327 MHz, and 55 Jansky at 238 MHz. The spectral index between the two extreme bands is then 1.2, and 1.24 between 74 and 238 MHz. Conservatively allowing an error of 50 % on the 74 MHz observation, we find a spectral index between 1.0 and 1.5. Thus we adopt 1.24 for further calculations, but we checked that the conclusions do not change if the spectral index is varied within these limits. It was noted that the spectral index of the lobe around the hotspots is around 0.5 (Lazio et al. 2006), and we expect the cavity spectral index to be much steeper than 0.5 containing an older electron population.

Using the mentioned equipartition argument we calculated the plasma properties for given flux density, spectral index, filling factor unity, and the lower integral limit of the synchrotron luminosity, 1 GeV. This is reasonable given the characteristic electron energy at 74 MHz with a magnetic field of  $17 \mu\text{G}$  is 8.9 GeV. We find  $1.18 \times 10^{-11} \text{ erg/cm}^3$  for the magnetic field energy density, and  $1.58 \times 10^{-11} \text{ dyne/cm}^2$  for the total relativistic plasma pressure, and a magnetic field of  $17.2 \mu\text{G}$ . The total non-thermal pressure we calculated falls short to make up for the missing thermal pressure in the previous section. However, we stress that what we calculated is the *minimum* pressure. Uncertainties could modify our scenario, for example, a higher proton energy ratio such as  $k=100$ , would increase the non-thermal pressure up to 46 % of the thermal pressure compared to 7 % as in our case. Other open factors which influence results are the geometry of the volume element as mentioned earlier, and the lower integral limit for the total electron energy.

From these physical parameters and some further observables we can also derive information on the age of the cavity. One constraint is derived from the fact that the cavity filled with relativistic plasma is much lighter than the ambient medium, and we thus expect it to be buoyantly rising in the cluster potential (Churazov et al. 2000). Assuming the buoyant velocity can be calculated from  $v_b = 0.5 \sqrt{R/R_K}$  where  $v_k$  is the Kepler velocity, we obtain a buoyant rise time of 50 Myrs for the present distance,  $R=23 \text{ kpc}$ , of the bubble from the centre. We interpret this as an approximate upper limit of the bubble age as we would expect an older bubble to have moved to a larger radius. Here the cluster was modelled with an isothermal  $\beta$  profile (Smith et al. 2002) with core radius  $29''$  and  $\beta=0.67$ , and the cavity volume contains negligible thermal plasma.

We can estimate the minimum age for this cavity assuming that electrons lose most of their energy through synchrotron ra-



diation in the magnetic field. If we adopt the break frequency at 750 MHz determined by Carilli et al. (1991) and our results for the magnetic field strength in the cavity, we obtain a spectral age of 24 Myrs. It is interesting that the spectral age map in Fig. 8 of Carilli et al. (1991) shows the X-ray cavity region as the oldest electron population in the core of Cyg A. This fits together with our suggestion below that the X-ray cavity was created earlier than the current jets, possibly by a less energetic feedback event.

## 5. Discussion

We can now compare the estimated age of the X-ray cavity to the age of the jet and the radio lobes of Cyg A. The time duration of the present high power activity and the age of the radio lobes estimated from simulations and observations is about 30 Myrs (Krause 2005; Wilson et al. 2006). This is of similar order as the estimated cavity age, but the limits we derived above also allow the cavity to be older by easily a factor of two. This provides some constraining information for the search of the origin of the cavity. One possible explanation is that the cavity is part of the backflow of the relativistic plasma from the hotspot region. It might have been broken off from the main lobes by an instability or as proposed in Carilli et al. (1991) by deflection of the backflow. In this case the cavity and the lobes would be expected to be of similar age. However, this is dynamically not easily possible since the growth timescale of e.g. Rayleigh-Taylor instabilities is  $\geq 50$  Myrs, which is much larger than the age of the current radio source.

However, we offer another explanation, where the radio plasma in the cavity has been created in a previous phase of jet activity at lower power output. We envision a scenario where the effect of the jets is similar to those in the Perseus cluster, where two radio bubbles were inflated close to the nucleus, creating cavities in the X-ray emitting gas (Böhringer et al. 1993; Fabian et al. 2002). If the jets have had a more North-South direction, and if the radio bubbles have partly been pushed off and partly started to rise due to buoyancy, we would expect to observe a cavity towards the South like the one we see.

The enthalpy necessary to create the cavity can be used as an estimate of the AGN jet energy output in this past event. Assuming the enthalpy is given by  $4PV$  (with  $P$  the pressure,  $V$  the volume of the cavity) we find an energy output of the AGN of the order of  $2.2 \times 10^{59}$  erg. For an activity duration of the order of 5–30 Myrs, the AGN power output in form of mechanical energy amounts to  $\sim 2\text{--}14 \times 10^{44}$  erg/s. This is about two orders of magnitude below the current AGN power, well in line with the scenario where the jets have gently inflated bubbles close to the AGN rather than creating powerful jets that plough far out into the cluster ICM like at the present time.

We have further investigated this hypothesis with 3D-hydrodynamics simulations with the NIRVANA code (Ziegler 2008). With a static gravitational potential two jets are injected by adding energy, momentum and mass to a cylindrical region with a radius of 0.2 kpc. First, a low power jet ( $10^{45}$  erg/s) is injected along the Z-axis for 5 Myrs. After a 5 Myr break, the main jet ( $2 \times 10^{47}$  erg/s) is started and evolved for 7.8 Myr. We show the resulting emission measure map along with contours of the two jet tracers through the midplane in Fig. 4. Interestingly the X-ray cavities created by the first jets are preserved during the expansion of the main jet, and just pushed outwards. A characteristic feature of this model are the four bright regions, which appear due to the presence of the old cavities separating them in the middle. This bares a striking resemblance to the X-ray ob-

servation of Cyg A. The jet tracers show that the plasma of the first jet was pushed towards the edges. Lobe plasma from the second jet and some thermal plasma has filled the cavity and the second jet plasma dominates the cavity pressure. The amount of the latter might in reality be somewhat suppressed due to the stabilising effect of magnetic fields. If in fact new plasma refills the old cavity some of our above conclusions may be modified. At the simulation time of 7.8 Myr after launch of the main jets, they have not yet expanded to the presently observed size. The effects discussed here are, however, clearly demonstrated, which includes the approximate size of the cavity. Since the simulation employed  $1.6 \times 10^{59}$  erg for the first jet pair, this confirms our order of magnitude estimate of the energy of the previous event.

## 6. Conclusions

We have combined most of the available *Chandra* X-ray data to construct a very detailed image of the ICM in the central region of Cyg A. The region around the AGN is rich in structure and one of the most striking features is an X-ray cavity south of the nucleus which is reminiscent of similar cavities in other cool cores of galaxy clusters. A comparison of the X-ray image with radio maps from *VLA* and *LOFAR* observations shows that the cavity is filled with relativistic plasma with a total enthalpy of  $2.2 \times 10^{59}$  erg. The most natural explanation in our opinion of the radio plasma filled cavity is an origin from previous activity of the AGN before the present radio lobes and shocked ICM region were created, more than about 30 Myrs ago. The appearance of the cavity and the X-ray morphology in the centre of Cyg A is well reproduced by our simulation of this scenario. In this case the power of the jets at this earlier epoch was about 100 times lower than today also consistent with the simulation results. Thus Cygnus A would have been classified at this epoch as FR I radio source. If our interpretation is correct we have the first evidence that an FR II radio source today was an FR I source at an earlier time.

*Acknowledgements.* MK and HB acknowledge support by the cluster of excellence “Origin and Structure of the Universe” ([www.universe-cluster.de](http://www.universe-cluster.de)). HB and GC acknowledge support from the DfG Transregio Program TR 33. GC acknowledges support from Deutsches Zentrum für Luft und Raumfahrt (DLR). This research has made use of *VLA*, *LOFAR*, and *Chandra* data, and software provided by the Chandra X-ray Center (CXC), and NIRVANA code v3.5 developed by Udo Ziegler at the Leibniz-Institut für Astrophysik Potsdam.

## References

- Alexander, P., Brown, M. T., Scott, P. F., MNRAS 209, 851, 1984
- Alexander, P., Pooley, G. G., Cygnus A – Study of a Radio Galaxy, Cambridge University Press, 1996
- Böhringer, H., Voges, W., Fabian, A. C. et al., MNRAS, 264, 25, 1993
- Carilli, C. L., Perley, R. A., Dreher, J. W. ApJ 334, L73, 1988
- Carilli, C. L., Perley, R. A., Dreher, W. W., Leahy, J. P., ApJ, 383, 554, 1991
- Carilli, C. L., Perley, R. A., Harris, D. E., MNRAS 270, 173, 1994
- Carilli, C. L., Barthel, P. D., A & AR, 7, 1, 1996
- Churazov, E., Forman, W., Jones, C., Böhringer, H., A & A, 356, 788, 2000
- Clarke, D. A., Harris, D. E., Carilli, C. L., MNRAS, 284, 981, 1997
- Fabian, A. C., Sanders, J. S., Crawford, C. S. et al., MNRAS, 331, 369, 2002
- Harris, D. E., Carilli, C. L., Perley, R. A., Nature, 367, 713, 1994
- Kaiser, C. R., Alexander, P., MNRAS, 305, 707, 1999
- Krause, M., A&A, 398, 113, 2003
- Krause, M., A&A, 431, 45, 2005
- Lazio, T. J. W., et al., ApJ, 642, L33, 2006
- McKean, J., et al., arXiv:1106.1041, 2011
- McNamara, B., Nulsen, P., ARA&A, 45, 117M, 2007
- Pacholczyk, Radio Astrophysics, Freeman, 1970
- Smith, D. A., Wilson, A. S., Arnaud, K. A., et al., ApJ, 565, 195, 2002
- Wilson, A. S., Smith, D. A., Young, A. J., ApJ, L9, 2006
- Wilson, A. S., Young, A. J., Shopbell, P. L., ApJ, L27, 2000

Yaji, Y., Tashiro, M., Isobe, N. et al., *ApJ*, 714, 37, 2010

Ziegler, U., *Computer Physics Communications*, 179, 227, 2008